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Dynamic Transconductance Dispersion Characterization of Channel Hot Carrier Stressed 0.25- μm AlGaIn/GaN HEMTs

Marco Silvestri, *Member, IEEE*, Michael J. Uren, *Member, IEEE*, and Martin Kuball

Abstract— Using the dynamic transconductance frequency dispersion technique, we characterize unstressed and hot electron stressed short channel AlGaIn/GaN High Electron Mobility Transistors (HEMT). The results reported in this letter demonstrate that the stress-induced degradation in DC and pulsed characteristics is unlikely to be ascribable to sizable trap generation at the AlGaIn/GaN interface.

Index Terms— HEMT, hot carriers, interface traps, reliability

I. INTRODUCTION

AlGaIn/GaN High Electron Mobility Transistors (HEMT) are among the most promising candidates for future high power switching and microwave systems. However, the long-term reliability of such devices is still under investigation. In particular, the physical location and activation energy of hot electron induced traps is still debated [1], [2]. Impact ionization and the resulting defects in AlGaIn/GaN HEMTs have been observed by different groups using optical and electro-optical techniques but providing different interpretations and models [2]–[4]. Conductance techniques are often used to electrically evaluate trap characteristics in large area MOS capacitors [5]–[7], however in HEMTs these become inaccurate in the case of short channel devices due to the weak capacitance signal offered by the small gate area. The use of transconductance (g_m) frequency dispersion to characterize traps has been proposed in several papers for both GaN and GaAs MESFETs [8], [9]. However, all the previous analyses focused on the real part of the measured g_m , not exploiting its imaginary part. In fact, it has been theoretically demonstrated that the imaginary part of the inverse of the g_m is conveniently related to the equivalent parallel trap admittance, and experimentally evaluated on silicon on insulator MOSFETs [10], [11]. As a consequence, any trap dynamic loss is reflected in the drain current via the device g_m without any need to measure the transistor capacitance. To date, this approach has not been taken advantage of for reliability studies of AlGaIn/GaN HEMTs. In particular, the presence of

channel hot carrier (CHC) induced traps can be assessed at or near the heterojunction interface which is often proposed as the location degraded by hot electrons [2], [12]. For the devices and stress conditions reported in this letter, we demonstrate that hot carrier stress does not result in a sizable density of traps at the heterointerface despite producing significant device degradation.

II. EXPERIMENTAL SETUP AND DEVICES

AlGaIn/GaN HEMTs grown by metal-organic vapor phase epitaxy on SiC substrate and fabricated into silicon nitride passivated devices with 4 μm source-drain gap, T-gates of 0.25 μm length, and 26-nm AlGaIn layer thickness were studied. Iron was incorporated into GaN during growth with a residual density of 10^{17} cm^{-3} in the channel region. The frequency response was evaluated with a Solartron 1255A Frequency Response Analyzer (FRA) in the range between 1 Hz and 100 kHz. The measurement system used in this work is sketched in the inset of Fig. 3a. The HEMT is biased in the sub-threshold region in order to minimise shorting effects of the inversion layer capacitance, and the gate voltage is modulated with a low AC signal (10 mV). The device is operated in the ohmic regime with a drain bias of 50 mV and the source current measured with a wideband, low-noise current to voltage (I - V) converter. The frequency dispersion was measured over the temperature range from 20°C to 80°C. Devices were CHC stressed at $V_{gs} = -2\text{V}$ and $V_{ds} = 20\text{V}$ in the semi-ON condition, which has been reported to be the conditions which maximise hot-electron damage [2]. Electrical DC characterisation and stress were performed with an Agilent 4156A parameter analyzer. Pulsed current-voltage characteristics have been measured with a Dynamic I-V Analyzer (DIVA) [13].

III. RESULTS AND DISCUSSION

Fig. 1 shows the DC I_{ds} - V_{gs} characteristic as well as the transconductance before and after CHC stress. After stress, the maximum drain current ($V_{gs}=0\text{V}$) decreased by about 30% and the transconductance peak by 20%, with about +100 mV pinch-off voltage shift. Fig. 2 reports the DC and the pulsed I_{ds} - V_{ds} characteristics before and after CHC stress. Following stress, there was no obvious change in pinch-off voltage under pulse conditions but the transient increase in R_{on} was up to 40% and there was a corresponding transient reduction in the

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M. Silvestri, M. J. Uren, and M. Kuball are with the Center for Device Thermography and Reliability (CDTR), H.H. Wills Physics Laboratory, University of Bristol, BS8 1TL, Bristol, UK; e-mail: marco.silvestri@bristol.ac.uk.

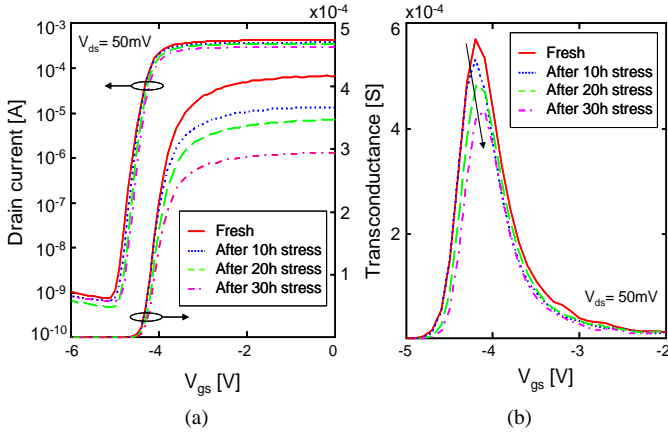


Fig. 1. DC drain current (a) and transconductance (b) vs. V_{gs} of AlGaIn/GaN HEMTs before and during CHC stress; width $2 \times 50 \mu\text{m}$.

saturation current. This suggests that the location of these stress-induced traps was not under the gate, but located in the proximity of the drain either on the surface or close to the AlGaIn/GaN interface.

In order to characterize the origin of the degradation, i.e., whether interface traps are generated by CHC, dynamic transconductance dispersion measurements were performed. Fig. 3a shows the g_m phase shift versus frequency measured at different temperatures in an unstressed device around the same value of $g_m \sim 4 \times 10^{-5} \text{ S}$ to enable easy comparison. There is a distinct peak in the phase shift; a corresponding small increase of g_m with frequency was observed which reflects the same physical mechanism but is much less clearly apparent. This demonstrates the effectiveness of measuring the dispersion in phase rather than g_m . In fact, the trap conductance G_p/ω , assuming a constant mobility, is related to the phase shift through the imaginary part of the inverse of g_m through the equation $G_p/\omega = -qC_{\text{barrier}}I_{ds}(kT)^{-1}\text{Im}(1/g_m)$, [11], where q is the electronic charge, C_{barrier} is the AlGaIn barrier capacitance, I_{ds} is the drain current, k the Boltzmann's constant, T the temperature in Kelvin. Using the data shown in Fig. 3a, the trap conductance, G_p/ω , was determined and is illustrated in Fig. 3b as a function of frequency for the different temperatures for an unstressed device. This temperature dependent phase shift peak indicates the presence of slow traps in or close to the AlGaIn/GaN channel in agreement with [14]. However the peak frequency did not vary with the DC gate bias at any temperature, and this necessarily means that these are not preferentially located at or close to the interface itself. This observation arises because the characteristic trap-time τ for interface states is inversely proportional to the density n_s of electrons in the channel through the relation $\tau = 1/v_{th}\sigma_t n_s$, where v_{th} is the thermal velocity, and σ_t the trap capture cross-section. Consequently, any change in the DC gate voltage results in a change in n_s and hence would change the peak frequency.

Data reported in Fig. 3b was well fitted using the model $G_p/\omega = qD_t(2\omega\tau)^{-1}\{\ln[1+(\omega\tau)^2]\}$, representing the conductance G_p/ω for a continuum of trap energy levels and for a given areal density D_t and characteristic time constant τ [5]. The areal density of traps extracted from the unstressed G_p/ω peak in Fig. 3b was $\sim 7 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$. Moreover, from the shift of

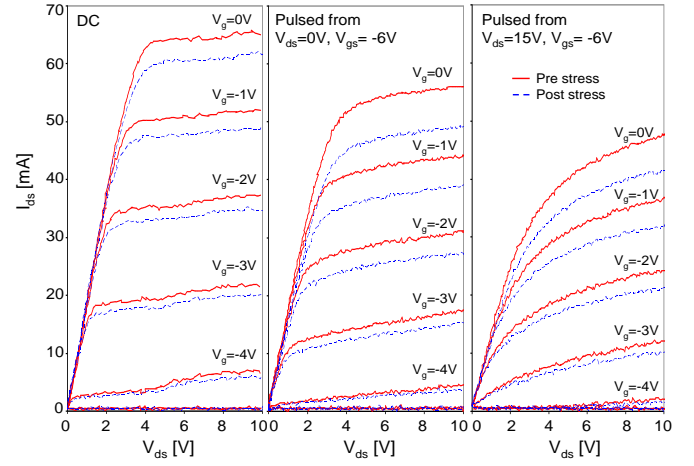


Fig. 2. DC and pulsed drain current vs. V_{ds} of AlGaIn/GaN HEMTs before and after CHC stress; width $2 \times 50 \mu\text{m}$.

the G_p/ω peak with temperature we determined an activation energy of 0.7 eV as reported in the inset of Fig. 3b.

Concerning the impact of hot carrier stress on trap generation, the conductance extracted before and after CHC stress is reported in Fig. 4a, showing little change with stress. The trap areal density as a function of the drain current was determined as shown in Fig. 4b, indicating perhaps a slight increase after stress up to $\sim 1 \times 10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$. As before, no DC-bias dependent conductance was observed.

In contrast to interface traps, bulk traps, either defects distributed within the AlGaIn barrier or the GaN buffer would not show a distinct bias dependence as observed in our measurements (see the inset to Fig. 4a). Assuming these are GaN bulk traps 0.7 eV below the conduction band, gives a cross-section of 10^{-12} cm^2 . This is reasonably consistent with published energy levels for Fe in GaN but the cross-section is much larger [15].

The dynamic g_m measurement does not show any indication of interface traps either before or after stress. We can conceive of three possibilities as to why we cannot see any such defects. Firstly the defects may have a cross-section such that they cannot respond in the accessible measurement time window. We estimate that we would have easily observed any interface traps with a density $> 10^{10} \text{ cm}^{-2} \text{ eV}^{-1}$ and cross-section between 10^{-19} and 10^{-15} cm^2 not hidden by the bulk trap response. This spans the range for such defects seen in other systems. Secondly, the interface traps may not form a continuum in energy but exist at a discrete energy level outside the range of surface Fermi level accessed in this study of about 0.1 eV to 0.4 eV below the conduction band. Or thirdly, any stress induced interface traps are created in the ungated drain-gate access region well away from the gate corner so that their occupancy can not be modulated during measurements. All of these are possible, but it strongly constrains the location and properties of such AlGaIn/GaN interface states. The CHC performance degradation reported in this work is similar in degree to that reported by other authors [2], [16]. CHC has previously been suggested to result in interface trap formation, but based on the results reported here, it is unlikely to be creating interface traps under the gate or in the vicinity of the

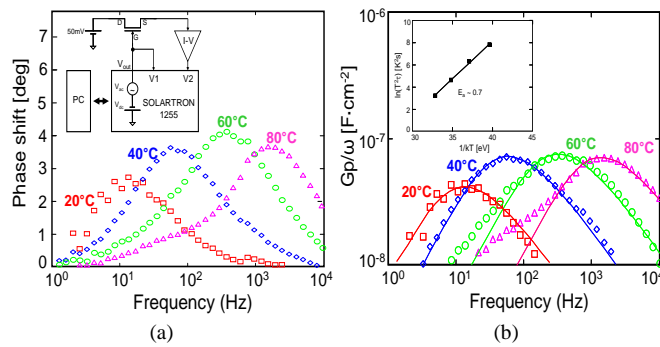


Fig. 3. (a) Measured phase shift dispersion and (b) Extracted conductance G_p/ω vs. frequency at different temperatures for unstressed device fitted with a continuum model. The extracted activation energy is about 0.7 eV as reported in the inset of (b).

gate corner. Based on this evidence and on the results of Fig. 1, we believe the traps are most likely to be located at the AlGaIn surface.

In conclusion, electronic traps in AlGaIn/GaN HEMTs have been measured by means of the dynamic transconductance frequency dispersion technique. This approach allows information to be gained on traps under quasi-equilibrium conditions in short-channel devices. The studied devices showed the signature of bulk trapping with activation energy of 0.7 eV consistent with the energy level for Fe-impurity in GaN. For the conditions reported in this work we found no evidence for interface traps either before or after CHC stress, whereas pulse measurements suggested that the damage is more likely to be surface related.

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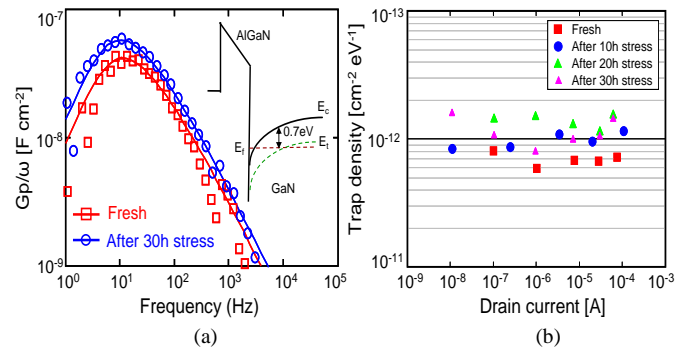


Fig. 4. (a) Bulk trap conductance vs. frequency before and after CHC stress; (b) Extracted trap densities vs. drain current before and during CHC stress.

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